Proceedings of the 15th International Symposium on Plasma Chemistry, edited by A. Bouchoule, J.M. Pouvesle, A.L. Thomann, J.M. Bauchire, and E. Robert (Orleans, France 2001), Vol. 1, pp. 173-178.

LARGE-AREA PLASMAS PRODUCED BY SHEET ELECTRON BEAMS

Richard F. Fernsler[1], Wallace M. Manheimer[1], Robert A. Meger[1], Martin Lampe[1], Darrin Leonhardt[1], Scott G. Walton[2], David D. Blackwell[2], and Donald P. Murphy[1]

[1]Naval Research Laboratory, Plasma Physics Division, Washington DC, USA 20375
[2]NRL/NRC Postdoctoral Research Associate

Abstract

A new type of reactor, termed the Large-Area Plasma Processing System (LAPPS), is being developed as a source for materials processing. Unlike most plasma sources, LAPPS uses a magnetically confined, sheet electron beam to produce a thin, planar plasma between two processing substrates. This approach offers several advantages over other reactors, including high plasma uniformity over large area (1 m^2 or more), efficient ionization and dissociation of all gases, independent control of the ion and radical fluxes, and cold plasma electrons.

1. Introduction

New plasma sources are continually being sought in an ongoing effort to improve materials processing in areas like etching, deposition and surface treatment [1]. Most sources being studied today produce ionization by heating plasma electrons with electromagnetic fields. The heating mechanisms include capacitive rf fields [2], inductive rf fields [3], electron cyclotron resonance [4], helicon waves [5], and surface waves [6]. The gas ionization rate in these sources depends on the plasma electron density n_p and temperature T_e, and typically electron temperatures of several eV or more are required to ionize the gas.

By contrast, an electron beam produces ionization at a rate determined by the beam energy and current density. Since the beam rather than plasma determines the ionization rate, greater control over the plasma is possible [7-9]. Moreover, beam ionization is more efficient than plasma ionization, and the plasma created by the beam is relatively cold, $T_e \leq 0.5$ eV. To take advantage of these attributes, a device termed the Large-Area Plasma Processing System (LAPPS) has been developed [8, 9]. This device uses a sheet electron beam with an energy of few keV and a current density ≥ 10 mA/cm^2 to produce large, planar plasmas with densities up to 10^{12} cm^{-3}. The plasmas are only a few cm thick but are up to 1 m long by 1 m wide on each side. A longitudinal magnetic field ~ 200 G is used to confine the beam transversely.

In this report, a theoretical comparison of LAPPS to conventional sources is given. A companion paper [10] describes the LAPPS device and experiments.

2. Plasma Production

The ion density n_p produced by a plasma source is determined in steady state by a balance between the volumetric gas ionization rate S_i and the various ion loss processes,

$$S_i = \beta n_p^2 - D_a \nabla^2 n_p \,. \qquad (1)$$

Proceedings of the 15th International Symposium on Plasma Chemistry, edited by A. Bouchoule, J.M. Pouvesle, A.L. Thomann, J.M. Bauchire, and E. Robert (Orleans, France 2001), Vol. 1, pp. 173-178.

Here β is the ion recombination coefficient, and D_a is the ambipolar diffusion coefficient. In conventional sources, an electric field is applied to heat the plasma electrons in order to ionize a background gas. If the degree of gas excitation is low, the ionization rate is given by $S_i = n_p N f_i(T_e)$, where N is the gas density, T_e is the local electron temperature, and $f_i(T_e)$ equals an average of the electron ionization cross section over the electron velocity distribution. Because $f_i(T_e)$ is a strong function of T_e, the temperature is tightly constrained and typically lies between 2 and 5 eV. Moreover, if T_e is constant in space and recombination is weak, T_e is a decreasing function of Nl alone, where l is a characteristic system size. The discharge power P_d then determines the plasma density n_p but not T_e.

For an electron beam, the gas ionization rate is determined by the beam rather than the plasma and is given by

$$S_i = \frac{j_b}{e} N \sigma_i(\varepsilon_b) \, . \tag{2}$$

Here j_b is the beam current density, ε_b is the beam energy, and $\sigma_i(\varepsilon_b)$ is the beam ionization cross section, including the cascade contribution. The range of the beam electrons is given by

$$R_b \approx \frac{\varepsilon_b}{2 N \sigma_i(\varepsilon_b) \varepsilon_i} \, , \tag{3}$$

where $\varepsilon_i \cong 30$ eV is the mean energy deposited in the gas per ionization event. For example, in a gas like nitrogen, the effective ionization cross section is $\sigma_i \cong 10^{-16}$ cm^{-2} at $\varepsilon_b = 2$ keV, and therefore the range is $R_b \cong 3$ m at 30 mtorr gas pressure ($N \cong 10^{15}$ cm^{-3}). The beam energy ε_b thus falls only modestly over propagation distances $l \leq 1$ m, and hence the ionization rate S_i is approximately constant if the beam is magnetically confined. In molecular gases like nitrogen, the electron-ion recombination coefficient is large, $\beta \sim 10^{-7}$ cm^3/s, and a beam with a current density $j_b \cong 15$ mA/cm^2 is then needed to produce a plasma density $n_p = 3 \times 10^{11}$ cm^{-3}, according to Eqs. (1) and (2). Less current is needed at higher gas pressures or in noble gases like argon where $\beta \cong 0$. These parameters are typical of those used in LAPPS.

3. Electron Temperature

The electron temperature T_e is important in processing because it affects both the plasma chemistry and ion anisotropy [1]. While T_e must be high in conventional sources to effect ionization, T_e is low in beam-produced plasmas because plasma ionization is weak by definition. That is, for a given total ionization rate, plasma ionization is weak whenever beam ionization is appreciable. Hence, T_e must be low in beam-produced plasmas.

To estimate T_e, divide the electrons into two energy bins. Electrons in the first bin have energies greater than the ionization potential W_i of the gas molecules, while electrons in the second bin have energies at or below W_i. Electrons in the first bin are small in number but are responsible for ionizing the gas and maintaining the plasma. Electrons in the second bin are far more populous and constitute the bulk of the plasma, and they thus control the electrodynamic fields and ion dynamics. Electrons from the first bin drop into the "plasma" bin once their energy falls below W_i, and these electrons thus continuously repopulate the plasma with a mean initial energy roughly equal to $0.5W_i$. In the absence of external fields, the average electron temperature is therefore determined by the energy-balance equation,

$$n_p N f_c(T_e) \approx 0.5 W_i \langle S_i \rangle = 0.5 W_i \left\langle \beta n_p^2 - D_a \nabla^2 n_p \right\rangle , \tag{4}$$

where the brackets denote an average over the plasma volume and $N f_c(T_e)$ is the rate at which plasma electrons lose energy to collisions with neutrals. Although the plasma loss rate again

Proceedings of the 15th International Symposium on Plasma Chemistry, edited by A. Bouchoule, J.M. Pouvesle, A.L. Thomann, J.M. Bauchire, and E. Robert (Orleans, France 2001), Vol. 1, pp. 173-178.

determines T_e, the temperature is now low, in agreement with experiment [10]. In particular, $T_e \leq 0.5$ eV in the molecular gases used for processing. In many halogen gases, dissociative electron attachment becomes large at these temperatures, and therefore plasmas consisting mainly of positive and negative ions can be continuously created. Such plasmas have been shown to improve ion anisotropy in deep trenches [11]. At the same time, external fields can be applied to raise T_e in order to change, for example, the plasma chemistry or ion dynamics.

4. Stability

Equation (4) underestimates T_e if the beam is unstable, since unstable beams transfer energy rapidly to the plasma. The fastest-growing and therefore most dangerous instability is the two-stream instability, and this instability is suppressed only if the momentum-transfer collision frequency of the plasma electrons is large [8],

$$\nu_{pe} > 2\pi\omega_p \left(\frac{n_b}{n_p} \right). \tag{5}$$

Here $\omega_p = (4\pi e^2 n_p/m_e)^{1/2}$ is the plasma frequency, $n_b << n_p$ is the beam density, and m_e is the electron mass. Condition (5) is usually met in processing gases provided the degree of gas ionization is low, $n_p/N < 10^{-3}$. Electron beams are thus capable of producing cold plasma down to gas pressures ~ 30 mtorr if $n_p < 10^{12}$ cm^{-3}, and down to ~ 3 mtorr if $n_p < 10^{11}$ cm^{-3}. At much higher densities or lower pressures, the beam ceases to propagate.

5. Efficiency

The ionization efficiency of a source is given by $\eta = W_i/\varepsilon_i$, where ε_i is the mean energy deposited in the gas per ionization event. In conventional sources, ε_i is a function of T_e alone if the degree of gas excitation is low. To illustrate, consider the plot of $\eta(T_e)$ in Fig. 1 for nitrogen. This plot was obtained by setting $\varepsilon_i = eE/\alpha$, where the Townsend coefficient α represents the ionization generated per cm of longitudinal travel by an electron in an electric field E. Swarm data [12] and calculation [13] give the reduced Townsend coefficient α/N and the temperature (or more correctly, the characteristic energy) T_e as functions of the reduced field E/N. For nitrogen, the ionization potential is $W_i = 15.6$ eV.

Figure 1 indicates that the efficiency of conventional sources is low, $\eta << 1$, especially if T_e is small. This is because most plasma electrons do not have enough energy to ionize the gas, and therefore the bulk of the energy absorbed goes into low-lying gas excitation rather than ionization. Moreover, as already discussed, T_e is not a free parameter but depends on Nl and possibly n_p. Efficiency is thus low, *unless* Nl is small or the gas is highly excited.

By contrast, the ionization efficiency η_b of electron beams is constant and close to 50%, independent of the beam energy ε_b or current density j_b. For example, $\varepsilon_i \cong 34.5$ eV in nitrogen, and therefore $\eta_b \cong 0.45$. The efficiency is high because all of the beam electrons can ionize the gas, and because the ionization cross sections exceed the excitation cross sections at high energy. The overall efficiency is less, however, if the chamber length l is shorter than the beam range R_b, because the beam then exits the processing region before losing all its energy; see Section 7 for further discussion. A compensating effect in LAPPS is the large ratio of processing area to plasma volume. Since the power needed scales with the number of plasma electrons present, decreasing the volume decreases the power required. Thin, planar plasmas like those in LAPPS thus require far less power per processing area. Although energy

Proceedings of the 15th International Symposium on Plasma Chemistry, edited by A. Bouchoule, J.M. Pouvesle, A.L. Thomann, J.M. Bauchire, and E. Robert (Orleans, France 2001), Vol. 1, pp. 173-178.

efficiency is relatively unimportant in today's devices, it is likely to become important as the processing area, power demand, and heating load rise.

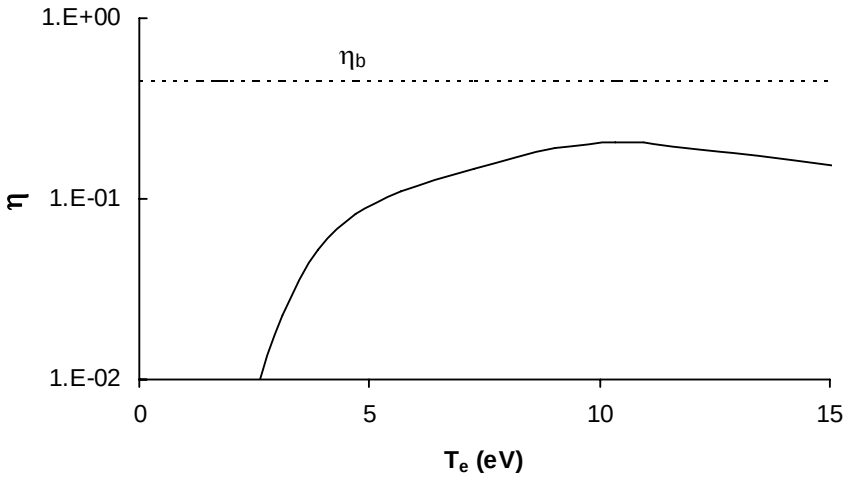

Figure 1. Ionization efficiency $\eta \equiv \alpha W_i/eE$ as a function of T_e in a nitrogen discharge. The line $\eta_b \cong 0.45$ is the ionization efficiency of electron beams.

6. Control

Plasma processing often requires multiple steps using different fluxes of ions and free radicals, and therefore independent control of the particle fluxes is desirable. However, such control is difficult to achieve in conventional sources, because T_e is largely predetermined. In addition, plasma electrons preferentially attack those species having the lowest ionization and dissociation energies, and therefore the fluxes are not directly tied to the gas composition.

By contrast, electron beams attack all species efficiently and at rates approximately proportional to the concentrations. In addition, beams can generate large fluxes of radicals, because most of the energy not going into ionization goes into gas dissociation. The gas composition thus determines the relative radical fluxes, while the gas density N and beam current density j_b determine the total flux. One possible problem is that electron beams can fragment complex gases *too* well, thus producing unwanted radicals. However, fragmentation from dissociative electron-ion recombination can pose even more of a problem in dense plasmas, independent of the ionization source.

Magnetically confined beams are well localized, and therefore the processing stage can be set at a specified distance δx from the ionization region. Recombination causes the ion flux to decreases with δx, and at large δx one can show from Eq. (1) that the flux reaching the stage is restricted to [9]

$$F_i = -D_a \nabla n_p \leq 35 \frac{D_a^2}{\beta(\delta x)^3}. \tag{6}$$

Moreover, the magnetic field B limits the ambipolar diffusion coefficient to [9]

$$D_a \leq \frac{T_e}{M_i \nu_i + m_e \omega_{ce}^2/\nu_e}. \tag{7}$$

Here M_i is the ion mass, ν_i is the ion collision frequency, and $\omega_{ce} = eB/m_e c$ is the electron cyclotron frequency. When T_e and N are low, the collision frequencies ν_i and ν_e are small, and

Proceedings of the 15th International Symposium on Plasma Chemistry, edited by A. Bouchoule, J.M. Pouvesle, A.L. Thomann, J.M. Bauchire, and E. Robert (Orleans, France 2001), Vol. 1, pp. 173-178.

therefore $D_a \rightarrow \nu_e T_e / r_o B^2$, where $r_o = e^2/m_e c^2$ is the classical electron radius. Increasing the standoff distance δx or the magnetic field B thus reduces the ion flux F_i reaching the substrate.

At the same time, dissociative recombination *increases* the radical flux, by converting each molecular ion into two or more radicals. Assuming two radicals are produced per dissociation or recombination event, the radical flux varies outside the beam as

$$F_r = \frac{I_b}{e} N(2\sigma_d + \sigma_i) - 2F_i \rightarrow \frac{I_b}{e} N(2\sigma_d + \sigma_i) - 70 \frac{D_a^2}{\beta(\delta x)^3}, \tag{8}$$

where I_b equals j_b integrated over the beam half-thickness and σ_d is the cross section for beam dissociation. Thus, increasing I_b, B or δx increases the radical flux F_r at the processing stage.

Equations (6)-(8) indicate that the ion and radical fluxes can be adjusted independently by varying the beam current I_b, the standoff distance δx, the magnetic field B, and/or the gas composition. Far less control is available with conventional sources, because in those sources the ionization region and rates readjust with the plasma environment.

7. Uniformity

In conventional sources, the volumetric ionization and dissociation rates depend on the plasma density n_p, which varies with position because of diffusion to the container walls. As a result, the ion and radical fluxes are uniform only over limited portions of the total plasma area, and much of the flux produced must often be wasted to achieve uniformity.

A similar tradeoff between uniformity and efficiency occurs with beam sources like LAPPS, but for different reasons. As the beam electrons collide with the gas molecules, the beam loses energy and spreads transversely. The beam energy ε_b and current density j_b thus vary with propagation distance z, and therefore the ionization rate S_i and fluxes vary as well.

To minimize beam spreading in LAPPS, a longitudinal magnetic field $B \sim 200$ G is applied. This field limits the electron gyroradius to $r_c < 1$ cm at beam energies $\varepsilon_b \leq 3$ keV. The beam then expands by less than r_c over its range R_b, and therefore j_b is nearly constant over distances $l < R_b$, provided the beam is a few cm or more thick initially [8]. The field B also *degrades* uniformity slightly, by slowing diffusion transverse to B. In particular, one can show from Eqs. (1) and (7) that diffusion causes the ion flux to vary in z by an amount limited to [9]

$$\frac{\delta F_i}{F_i} \leq \left(\frac{\Delta x}{l}\right)^2 \left(1 + \frac{m_e \omega_{ce}^2}{M_i \nu_i \nu_e}\right), \tag{9}$$

where $\Delta x > 2\delta x$ is the plasma thickness. The variation in ion flux F_i is thus modest as long as the plasma is sufficiently thin, $\Delta x << l$.

As the beam propagates, its energy ε_b falls and therefore the ionization cross section, $\sigma_i(\varepsilon_b) \propto \ln(\varepsilon_b)/\varepsilon_b$, rises with z. The ionization rate S_i and particle fluxes then increase as well, and for a single beam these variations are weak only if the beam range is long, $R_b >> l$. In that case, much of the beam energy is wasted in the beam dump. This tradeoff between uniformity and efficiency can be reduced to some extent by recovering the energy prior to the beam dump, by using two opposing beams similar to a Penning discharge, or by varying the gas density N in z to offset the rise in σ_b. Note that variations in N are common in processing systems, because of ion pumping and inhomogeneous gas flow.

Proceedings of the 15th International Symposium on Plasma Chemistry, edited by A. Bouchoule, J.M. Pouvesle, A.L. Thomann, J.M. Bauchire, and E. Robert (Orleans, France 2001), Vol. 1, pp. 173-178.

8. Summary

In this report we have shown that the use of a magnetically confined, sheet electron beam in the LAPPS reactor offers a number of advantages over conventional reactors. These advantages include: (i) high plasma uniformity over areas up to 1 m^2 or more; (ii) efficient gas ionization and dissociation; (iii) independent control of the ion and radical fluxes; (iv) low and potentially controllable electron temperature; and (v) wide operating range in gas type and pressure. No other plasma source is known to offer similar control, flexibility, and efficiency over such large area. Moreover, many of the predictions reported here have been confirmed experimentally [10]. In particular, LAPPS has been shown to generate plasmas with densities ranging from 10^{10} to above 10^{12} cm^{-3} over a wide range in gas pressure and type. The plasmas created were uniform to better than 10% over areas up to 60 cm by 60 cm, as dictated by the size of the electron beam and vacuum chamber. Furthermore, the electron temperature ranged from 0.3 eV in molecular gases to more than 1 eV in atomic gases, and plasmas containing large numbers of negative ions were produced in the halogen gas SF_6. Preliminary processing studies are now underway.

9. References

1. M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, New York, Wiley (1994).
2. V. A. Godyak, *Soviet Radio Frequency Discharge Research*, Delphi Associates, Falls Church, VA (1986).
3. J. Hopwood, *Plasma Sources Sci. Technol.* **1**, 109 (1992).
4. J. Amussen, *J. Vac. Sci. Technol.* A **7**, 883 (1989).
5. F. F. Chen, *Plasma Phys. Controlled Fusion* **33**, 339 (1991).
6. A. W. Trivelpiece and R. W. Gould, *J. Appl. Phys.* **30**, 1784 (1959).
7. M. J. Kushner, W. Collison and D. N. Ruzic, *J. Vac. Sci. Technol.* A **14**, 2094 (1996).
8. R. F. Fernsler, W. M. Manheimer, R. A. Meger, J. Mathew, D. P. Murphy, R. E. Pechacek and J. A. Gregor, *Phys. Plasmas* **5**, 2137 (1998).
9. W. M. Manheimer, R. F. Fernsler, M. Lampe and R. A. Meger, *Plasma Sources Sci. Technol.* **9**, 370 (2000).
10. R. A. Meger, *et al*., "Electron Beam Plasma Generation for Processing and Non-Equilibrium Plasma Applications," these proceedings.
11. T. H. Ahn, K. Nakamura and H. Sugai, *Plasma Sources Sci. Technol.* **5**, 139 (1996).
12. J. Dutton, *J. Phys. Chem. Ref. Data* **4**, 577 (1975).
13. K. I. Bakhov, L. P. Babich and I. M. Kutsyk, *IEEE Trans. Plasma Sci.* **28**, 1254 (2000).